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External Dose Estimates for Dolon Village: Application of the U.S./Russian Joint Methodology

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Methods to estimate external dose from radioactive fallout from nuclear tests have for many years depended on two types of data: measurements of exposure rate in air and an empirically derived power function to describe the change in exposure rate with time, Over the last four years, a working group with American and Russian participation has developed a bi-national joint methodology that offers an improved capability for estimating external dose. In this method, external dose is estimated using exposure rate functions derived from data from American nuclear tests similar in construction to SNTS (Semipalatinsk Nuclear Test Site) devices. For example, in this paper, we derive doses for test #1 (August 29, 1949) at the SNTS using an exposure rate function for the U.S. TRINITY test. For the case of test #1, the average external dose for a person in Dolon is estimated to have been about 0.5 Gy compared to 1 to 2 Gy estimated in other work. This prediction agrees better with reported EPR measurements in teeth from village residents and with measurements of TL signals in bricks from Dolon buildings. This report presents the basic elements of the joint methodology model for estimation of external dose received from SNTS fallout.

INTRODUCTION

Estimates of whole body radiation dose to inhabitants of villages near the Semipalatinsk nuclear test site have been made by several investigators.[1,2] The village of Dolon has long been known to have received some of the highest doses in this region, primarily as a result of the first test on August 29, 1949. Since 1999, experts in fallout dosimetry at the U.S. National Cancer Institute, the U.S. Dept. of Energy, and the University of Utah have collaborated with the Russian Institute of Biophysics to combine essential data and theory from the U.S. and Russia to develop a combined methodology to improve fallout dose estimation. The primary application of that method is for estimating individual doses to residents of villages near the Semipalatinsk Nuclear Test Site (SNTS), although it will likely have broader application to situations where fallout from nuclear explosions results in exposures over a wide range of distances from the detonation site.

The joint methodology, while not completely finalized on all aspects of internal dosimetry, has been essentially completed for external dosimetry. The methodology has been implemented to estimate external radiation doses to the population of Dolon and other nearby villages as part of an epidemiologic study now underway by the U.S. National Cancer Institute. This paper describes the essential elements of the external calculation methodology and summarizes estimated doses received by representative residents of Dolon.

METHODS

Many environmental radiation-exposure models use integration of measured or estimated exposure rates for the duration of a defined exposure period as the basis for external dose estimation. Most historical dose reconstructions use a variation of the power function, t^{-n}, to describe the rate of change of exposure rate with time and are characterized either by a constant power, e.g., $t^{-1.2}$,[3] or by a piecewise continuous dependence where n is constant only within specified time intervals.[2,4,5]

As a replacement for the well known t^{-n} power function, the time-dependence of the exposure rate is described in the U.S./Russian Joint Methodology by a 10-term exponential

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function similar to that developed for Nevada Test Site tests.[6] The data used to fit the exposure rate functions were calculated at Lawrence Livermore Laboratory and were validated against measurement data collected following American nuclear tests of different constructions and nuclear fuels.[7,8]

For the joint methodology, we developed 10-term exponential functions to describe exposure rate with time for U.S. nuclear test devices of three different designs: (i) TRINITY for devices fueled with ^{239}Pu but surrounded by heavy steel and lead shielding, (ii) TURBALOY, a simulated weapon fueled by ^{238}U, and (iii) TESLA, for devices fueled by pure ^{239}Pu. The data used to fit these functions were derived and published by Hicks.[9,10] In addition, we modified the three shot-specific exposure-rate functions for differing degrees of fractionation based on considerations of wind speed and the maximum height of the cloud. We assigned one of the above-mentioned exposure rate functions to each test at the SNTS depending on which of these three U.S. tests was most similar in design and fuel.

In most methods for fallout dose estimation, some means to account for exposure during the passage of the cloud, for what is known as cloud immersion dose, is usually included in the calculation [see ref. 2, eq.(2)]. In the method discussed here, no explicit calculation is made of the cloud immersion dose, though the dose contribution during cloud passage is implicitly included. Cloud immersion dose is approximated here by integrating the exposure rate function from time of arrival of the leading edge of the fallout cloud until infinity (or other specified stopping point) instead of making separate calculations from time of fallout onset to fallout completion and summing that with the dose estimated from time of fallout completion until infinity. The reader should note that in most cases, neither the time of the initial onset of fallout, nor the time of the completion of fallout are precisely known, but are estimated based on available data.

Estimation of exposure rates, integral exposure, and whole-body dose. The exposure rate functions presented here are normalized (i.e., set equal to unity) at 12 hours post detonation as were the data used for fitting. The normalized exposure rate functions, NE(t), approximate the true change in exposure rates by the sum of ten exponential terms:

$$\mathrm{NE(t)} = \sum_{i=1}^{10} A_i e^{-\lambda_i t} \tag{1}$$

where NE(12) 1.0, the values of the parameters A_i and λ_i (h^{-1}) are determined from non-linear least squares fitting, and *t* is the time post-detonation (h).

With use of the formulation in eq. (1) and a measured or estimated exposure rate, $\dot{E}(\zeta)$ at time $t=\zeta$, the exposure rate can be estimated at any time $t=\zeta'$ (eq. 2):

$$\dot{E}(\zeta') = \dot{E}(\zeta)\frac{\mathrm{NE}(\zeta')}{\mathrm{NE}(\zeta)} \tag{2}$$

This allows, for example, calculation of the exposure rate at 12 h after detonation [i.e., $\dot{E}(12)$] from an exposure rate measurement $\dot{E}(\zeta)$ made at any time ζ.

With use of eq. (2) to estimate the exposure rate at 12 h post detonation, the integral exposure can be calculated from the fallout time of arrival (TOA, h) until infinity or to any specified stopping point with eq. (3). Note that since exposure rate was historically measured in units of roentgens (R) per unit time, the integral exposure is similarly calculated in units of roentgens.

$$\begin{aligned}\text{Exposure (R)} &= \int_{t=\mathrm{TOA}}^{t=t_2} \dot{E}(t)\,dt = \int_{t=\mathrm{TOA}}^{t=t_2} \dot{E}(12)\sum_{i=1}^{10} A_i e^{-\lambda_i t}\,dt \\ &= \dot{E}(12)\sum_{i=1}^{10}\left[\frac{A_i\ e^{-\lambda_i\,\mathrm{TOA}}}{\lambda_i} - \frac{A_i\ e^{-\lambda_i\,t_2}}{\lambda_i}\right] \\ &= \dot{E}(12)\sum_{i=1}^{10}\left[\frac{A_i\ e^{-\lambda_i\,\mathrm{TOA}}}{\lambda_i}\right]\text{if } t_2=\infty \end{aligned} \tag{3}$$

Equation (3) can be rewritten in shorthand notation:

$$\text{Exposure (R)} = \dot{E}(12)\left(\frac{E}{\dot{E}(12)}\right) \tag{4}$$

$$\text{where } = E/\dot{E}(12) = \sum_{i=1}^{10}\left[\frac{A_i\ e^{-\lambda_i\,\mathrm{TOA}}}{\lambda_i} - \frac{A_i\ e^{-\lambda_i\,t_2}}{\lambda_i}\right]$$

Estimation of whole-body radiation absorbed dose (Gy), considering time spent in and out of doors uses the result of eq. (4):

$$D_{ext}\ (\mathrm{Gy}) = \dot{E}(12)\left(\frac{E}{\dot{E}(12)}\right)\left[\frac{T_o}{24} + \left(\frac{24-T_o}{24}\right)\mathrm{SF}\right]\mathrm{DF} \tag{5}$$

where,

T_o = average time spent outdoors daily (h)

SF = building (home) shielding factor (≡ dose rate indoors/dose rate outdoors)

DF = dose factor for whole body absorbed dose (Gy per R)

Note that eq. (5) is an approximation that is based on the average amount of time spent indoors and outdoors. Further consideration is being given to modifying this model to account for time outdoors at the actual time of fallout deposition.

Input data for calculations. Data required for estimation of external doses to representative village residents include $\dot{E}(12)$ (R/h, extrapolated from time of measurement), TOA (for calculating $E/\dot{E}(12)$ in eq. 3), T_o (h/day, age-dependent), SF (unitless, dependent on house construction materials), and DF (Gy per R). The source and numerical values of the input data for test #1 in Dolon are discussed in the remainder of this section.

Table 1. Coefficients for exposure-rate function for TRINITY test (see eq. 1) assuming a refractory to volatile ratio of 3.0 (see text).

A_i	λ_i (h^{-1})
9.07E+01	2.09E+00
1.84E+01	6.98E–01
5.37E+00	3.50E–01
1.21E+00	1.23E–01
6.70E–01	3.92E–02
2.22E–01	9.07E–03
1.82E–02	2.74E–03
4.48E–03	4.20E–04
3.71E–06	7.95E–06
1.00E–08	4.73E–05

A measurement of exposure rate was reported to be 33 μR/s at H+173 h (=119 mR/h)[11] though 100 mR/h has also been reported.[12] In this work, the exposure rate at H+12 was estimated via eq. (2) using 100 mR/h as input data and a 10-term exposure rate function derived from the U.S. TRINITY test that incorporates minor modifications for weathering after the first few weeks and assumes a ratio of refractory to volatile nuclide activity in Dolon of 3.0. In this case, the TRINITY test was used as a surrogate for test #1 at the SNTS. Table 1 provides values of the coefficients we used for eq. (1). We have assumed fallout to have commenced in Dolon at 2.4 hours as reported elsewhere,[1] i.e., TOA = 2.4 h. For purposes of estimating doses to representative village residents, we assumed the average time spent outdoors daily (T_o) by a 5 yr old child to be about 4.5 hours per day and the number of hours spent outdoors by an adult in summer months to be about 16. In addition, we have assumed the shielding factor for wood houses in Dolon, as used by the Russian population, to be about 0.33.[1] Finally, we assume a dose factor of DF ≅ 6.6 mGy per R with about a 30% larger value for young children (as derived from[13,14]).

FINDINGS

Using eq. (2) and the exposure rate of 100 mR/h at H+173 gives an estimate of the exposure rate at H+12 of 1600 mR/h. The exposure rate at H+12 predicted via eq. (2) is about 16 times the value at H+173 h, while the exposure rate at 12 h post-detonation predicted by $t^{-1.2}$ is about 25 times the H+173 value (see Fig. 1). The predicted exposure rate by the power function is about 53% greater at H+12 than that predicted by the ten-term exponential and about 30% greater at TOA (H+2.4).

With the use of eq. (3) and the estimated exposure rate of 1600 mR/h at H+12, the integral exposure (from TOA to ∞) is estimated to be 122 R. For comparison, the integral exposure predicted by integration of the power function is about 204 R, a value 66% greater than using eq. (3).

For the purposes of this report, eq. (5) and the assump-

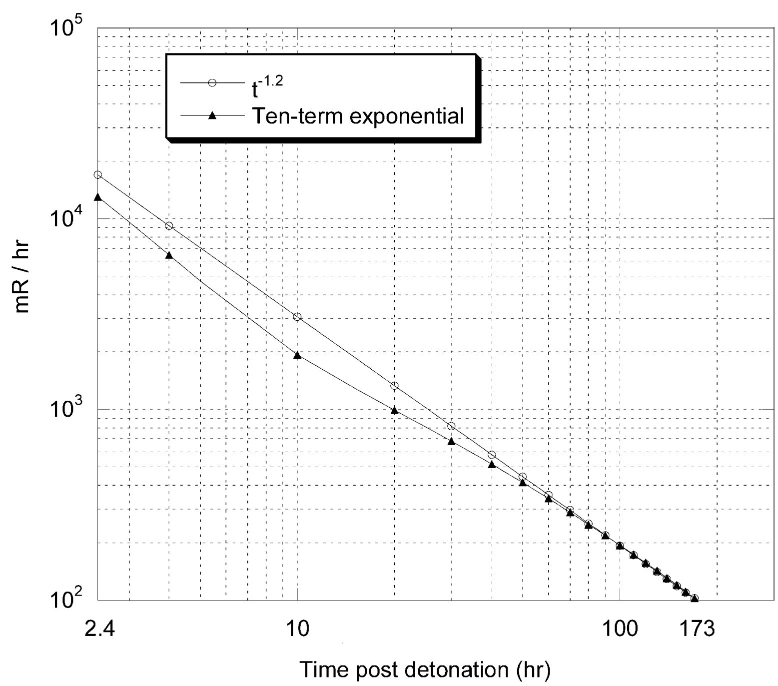

Fig. 1. Back extrapolation of 100 mR/h exposure rate at time of measurement (H+173 h) to time of fallout arrival (2.4 h) by two different models: $t^{-1.2}$ and ten-term exponential function.

tions discussed earlier were used to estimate external whole-body doses from test #1 to a representative 5 yr old and adult in Dolon. Those doses were 0.40 Gy and 0.63 Gy, respectively. For comparison, the external whole body dose estimated by integration of the $t^{-1.2}$ power function would be 0.68 Gy and 1.1 Gy for a child and an adult, respectively. Note that some publications using the simple power function have reported an external effective dose of 1.3 Sv[1] from test #1.

DISCUSSION

The example calculations shown here illustrate that estimation of the external whole-body dose by the joint U.S./Russian methodology results in lower estimates of dose than those from the often used power function of the form $t^{-1.2}$. The integral dose is proportional to the area under the exposure rate curve (see Fig. 1) and is less for the 10-term exponential function compared with the power function because of differences in shape of the function, especially during early times when the exposure rate is relatively high. Because test #1 at the SNTS was reported to be a copy of the TRINITY device in terms of fuel and design,[15] we believe that the exposure rate function for TRINITY provides more realistic values of integral dose than other functional descriptions for the time dependence of exposure rate.

An important issue not yet resolved is the most suitable value of the exposure rate in the village at the time of deposition. Not only is there is about a 20% difference between two reported values (33 μR/s and 100 mR/h), but more importantly, it is not known how well either value represents the dose rate in the village, how that dose rate might have varied over the area of the village where people lived, and whether its time dependence could have been significantly altered by rainfall, washoff, and penetration of fallout into the soil column.

Reported measurements of TL signals in brick and EPR signals in tooth enamel (see reference[2],Table 3) suggest that the integral exposure in Dolon may have been somewhat less than estimated here. One explanation could have been a lower initial exposure rate in the village as compared to the central axis of the trace where the original exposure rate measurements were made. The width of the plume at Dolon village may have been very narrow; that hypothesis has been investigated[16] using soil sample data. A second explanation could have been a more rapid than expected decrease in exposure rate due to weathering effects. Moderately heavy precipitation at the time of deposition, or immediately following could have washed fallout from the ground surface away from the site of the brick buildings or resulted in greater and more rapid penetration of the fallout into the soil column than assumed in our weathering approximation. Such phenomena would have reduced the integral exposure received by the bricks compared to our estimate. EPR measurements could be biased low due to a number of factors, e.g., failure to account for movements of individuals in and out of the village, which would likely have reduced the integral exposure each person received.

Two other tests were reported to have deposited fallout in Dolon, though the dose contributions from them were small in comparison to test #1. Using the methods and assumptions described here, we estimated that tests #19 (July 29, 1955) and #148 (August 7, 1962) contributed about 0.3 and 0.15 mGy (external whole-body dose), respectively, to a child at the time of exposure and about 0.4 and 0.2 mGy to an adult. For those tests, we used exposure rate functions developed from the U.S. test, TESLA, which was fueled by ^{239}Pu. In addition, we adjusted the exposure rate functions to simulate a refractory to volatile ratio of 2 and 0.5, respectively. As noted earlier, the joint U.S./Russian methodology estimates the refractory to volatile ratio at each location based on several variables, including wind speed and cloud height (a function of explosive yield).

CONCLUDING REMARKS

The results presented here should be considered as preliminary even though only minor changes to the U.S./Russian external dose estimation methodology are presently being contemplated. Our near term goals are to further evaluate recent measurements of biological and physical samples and determine how they should be used for corroboration of estimated doses, further analyze potential input data, and perform a quantitative uncertainty analysis.

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REFERENCES

1. Gordeev, K., Vasilenko, I., Lebedev, A., Bouville, A., Luckyanov, N., Simon, S. L., Stepanov, Y., Shinkarev, S., Anspaugh, L.. (2002) Fallout from nuclear tests: dosimetry in Kazakhstan. Radiat. Environ. Biophys. **41**: 61–67.
2. Gordeev, K., Shinkarev, S., Ilyin, L., Bouville, A., Hoshi, M., Luckyanov, N., Simon, S. L. (2006) Retrospective dose assessment for the population living in areas of local fallout from the Semipalatinsk Nuclear Test Site. Part I: External exposure. J. Radiat. Res. **47**: A129–A136.
3. Miller, C. F., Loeb, P. (1958) Ionization rate and photon pulse rate of fission products from slow neutron fission of U-235. USNRDL-TR-247. San Francisco, CA: U. S. Naval Radiological Defense Laboratory.
4. Leipunski, O. I. (1959) Gamma-radiation of an atomic detonation. Atomizdat (in Russian).

5. Larson, K. H., Neel, J. W., Hawthorne, H. A., Mork, H. M., Rowland, R. H., Baurmash, L., Lindberg, R. G., Olafson, J. H., Kowalewsky, B. W. (1966) Distribution, characteristics, and biotic availability of fallout, Operation Plumbbob. WT-1488. Los Angeles, CA: University of California at Los Angeles, Laboratory of Nuclear Medicine and Radiation Biology.
6. Henderson, R.W. (1991) Approximation of the Decay of Fission and Activation Product Mixtures. LA-11968-MS. Los Alamos, NM: Los Alamos National Laboratory.
7. Hicks, H. G. (1982) Calculation of the concentration of any radionuclide deposited on the ground by off-site fallout from a nuclear detonation. Health Phys. **42**: 585–600.
8. Hicks, H. G. (1990) Additional calculations of radionuclide production following nuclear explosions and Pu isotopic ratios for Nevada Test Site Events. Health Phys. **59**: 515–523.
9. Hicks, H. G. (1981) Results of calculations of external radiation exposure rates from fallout and the related radionuclide compositions. UCRL-53152, parts 1-8. Livermore, CA: Lawrence Livermore National Laboratory.
10. Hicks, H. G. (1985) Results of calculations of external radiation exposure rates from fallout and the related radionuclide compositions-the Trinity Event. UCRL-53705. Livermore, CA: Lawrence Livermore National Laboratory.
11. Shoiket, Y. N., Kiselev, V. I., Loborev, V. M., Sudakov, V. V., Algazin, A. I., Demin, V. F., Lagutin, A. A. (1998) The 29 August, 1949 nuclear test, radioactive fallout on the Altai region. Barnaul, Russia: Institute of Regional Medico-Ecological Problems.
12. Gordeev, K. I. (2001) Radiation exposure to the population of the Semipalatinsk region from Semipalatinsk weapons tests. Part IV. Assessment of the realistic doses to whole-body from external gamma irradiation and doses to thyroid from internal irradiation for the populations living in the number of settlements of Kazakhstan as a result of radiation exposure from nuclear explosions conducted at the Semipalatinsk Polygon. Report to the National Cancer Institute. Bethesda, MD: National Cancer Institute.
13. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (1993) 1993 Report to the General Assembly, with Scientific Annexes. UN publication E.94.IX.2. New York, NY: United Nations.
14. NCRP (1999) Recommended screening limits for contaminated surface soil and review of factors relevant to site-specific studies. NCRP Report. No. 129, Bethesda, MD: National Council on Radiation Protection and Measurements.
15. Rhodes, R. (1995) Dark Sun. The Making of the Hydrogen Bomb. New York, NY: Simon and Schuster Publishers.
16. Imanaka, T., Fukutani, S., Yamamoto, M., Sakaguchi, A., Hoshi, M. (2005) Width and center-axis location of the radioactive plume that passed over Dolon and nearby villages on the occasion of the first USSR A-bomb test in 1949. J. Radiat. Res. **46**: 395–399.

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